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THE GIGANTIC METEORITE OF 12 FEBRUARY 1947

By Academician V. G. Fesenkov

At the end of February 1947 the Academy of Sciences USSR received word from its Far Eastern base at Vladivostok that an enormous meteorite had fallen in the maritime taiga on the spurs of the Sikhote Alin range between Vladivostok and Khabarovsk; it had felled trees over a large area, and had formed numerous craters. The director of the geological section of the base, F. K. Shipulin, along with geologists of the Khabarovsk Geological Administration, examined the location, and found several meteoric fragments which were very similar in appearance to projectile splinters.

The physicomathematical division of the Academy of Sciences suggested that I conduct the investigation of the unprecedented phenomenon. In view of the almost complete lack of information about the circumstances of the fall, I had to organize an expedition at Vladivostok, where I arrived on 1 April with my fellow travellers, colleagues of the Institute of Astronomy of the Kazakh SSR; here I was awaited by Krinov, secretary of the Meteoritic Committee, Academy of Sciences USSR. Together with colleagues of the Far Eastern base whom I had invited, the group consisted of nine persons; to this group 12 sappers with two commanders were attached by order of the Maritime Military District Headquarters.

The maritime taiga, our destination, presents a very thick forest of numerous types of coniferous and deciduous trees, entangled with lianas and wild grape, with all sorts of shrubbery. This forest is choked with the fallen trunks of trees, which make travel extremely difficult. At the same time, there must be preserved in this dense taiga numerous traces of meteoritic bodies that have passed over. In low places, especially in the valleys of streams and rivers, the soil is very swampy. In summer visibility is limited to a few meters, as a result of which travel is possible only by

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preliminary reconnaissance. Mosquitoes and tiny gnats swarm in the moisture-saturated air; moreover, the taiga abounds in ticks, which appear in spring before the retreat of the snow. In summer, a search for meteorites in the taiga over an area of many square kilometers is practically impossible.

On the other hand, the search for meteorites is also impossible in winter, when the ground is covered with snow 1-2 meters deep. At the beginning of autumn, about the end of August, there are violent downpours here, which frequently produce floods. Consequently, there are only two periods for field work: early spring, between the melting of the snow and the development of vegetation; and late autumn and part of winter, before heavy snowfall.

Thus, the group of about 30, including secondary workers, had approximately one month to spend in the taiga at the spot where the meteorite fell. For this purpose it was necessary to transport about 3 tons of cargo including instruments, equipment, and provisions. This was possible only with the active cooperation of Party and Soviet organizations of the Maritime Kray.

First, it was necessary to collect evidence from the persons who witnessed the flight and fall of the meteorite while it was fresh in their memory; likewise, it was necessary to determine the best route to the meteorite, and to send sappers to the location to build shelter and do other preparatory work. This was done by two members of the expedition, Divari and Karimov, who travelled along water-logged roads and marshes for several hundred kilometers, and visited 52 populated places--collective farms, apiaries, machine-tractor stations, border outposts, etc.--and interrogated about 300 eyewitnesses. Then, with the aid of simple goniometers, the coordinates of the points of appearance and disappearance of the meteorites, according to the eyewitnesses, were measured in relation to terrestrial objects. I shall present one of the numerous statements recorded by Divari and Karimov.

Ashlaban, a forester, was in the taiga 15 km west of the place of fall, and was chopping down a tree. It was a clear, frosty morning. Suddenly he saw a second shadow appear from the tree and quickly turn around the trunk. Turning around, he saw a bright flying body twice as large as the sun, of a color similar to that obtained in electric welding. Numerous sparks of various colors flew from the incandescent head of the oblong form. Behind there streched a dark, swirling trail, which remained for several hours. In the passing light the trail seemed red in color. Approaching the horizon, the meteorite dropped sharply (it broke in two), and disappeared beyond the distant taiga. After a short time a noise was heard like the firing of many guns, and a dark pillar arose which remained until evening, gradually disappearing. No jarring of the ground or perceptible air wave was noted.

We succeeded in finding a number of persons who, according to watches verified by radio, noted the moment of fall of the meteorite almost exactly to the minute, namely, 10:35 Vladivostok time.

Plotting the observed trajectories of the meteorite in the atmosphere on a grid in gnomonic projection, it was possible to determine its actual movement in relation to the surface of the earth. It seemed that it was flying at an angle of 36 degrees to the horizon at an azimuth of 24 degrees east of true north. Its entire trajectory, from the moment of entrance into the atmosphere, passed over the territory of the USSR. The meteorite was moving in the same direction as the earth, and overtook it at a small angle to its orbit, at a speed of about 10 km per second. Such a comparatively low speed permitted it, unlike the famous Tungus meteorite of 30 June 1908, to reach the surface of the earth, disintegrating into an enormous number

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of lumps of various dimensions, which covered an area of tens of square kilo meters.

Examination of the crater field showed that the meteorite hit the surface of the earth much more steeply, at an angle of approximately 60 degrees, and almost exactly in the direction of the meridian, with a declination to the east of only 4 or 5 degrees. This is explained by the resistance of the air, which not only reduced the speed of movement of the meteorite, but also turned its trajectory in the plane of the meridian. We should note that the speed of transfer of atmosphere from west to east in the latitude of the meteorite was very close to the speed of sound.

Upon arrival at the place of fall the expedition discovered 106 craters and funnels.

All these craters were plotted on a map (1:2,000) on the basis of triangulation and theodolitic bearings. The interiors of the craters were heaped with fragments of the porphyries which lie in the place of fall of the meteorite at a shallow depth in the form of parallel layers and slightly slanted toward the horizon. The total volume of the hollow of the largest crater (No 1) was somewhat over 1,000 cu m. The material thrown out was distributed around this crater mainly in a western direction, corresponding to the relief of the locality.

The thickness of the solid cover thrown out, consisting of clay and fragments of porphyry, on the edge of Crater No 1 did not exceed 0.5 meters, and quickly decreased with the distance.

The calculation of the volume of the ejected material led to the same figure: about 1,000 cu m. If one takes into consideration the amount of clay and rock that fell back into the crater, then the conclusion must be drawn that from one crater (No 1), a few moments after the impact of the meteoritic body, about 5,000 tons of material were ejected. The material ejected from this crater (as from the others as well) was distributed rather evenly in the form of a comparatively thin layer over a distance considerably exceeding the diameter of the crater itself. Individual stones flew considerably farther, and were found at distances of hundreds of meters from the crater field. Crater No 1 is cup-shaped with an elevation of the rim corresponding to the relief of the locality. The rest of the large craters are cone-shaped depressions, sometimes with a small horizontal area in the center. All are heaped with shattered rock, and have almost no traces of trees.

The structure of the bottom, the internal profile, and the absence of banks in the craters of the Sikhote Alin meteorite present a sharp contrast to the form of the moon's craters. Therefore, one may say the experiment performed by nature itself in this phenomenon does not confirm the meteoritic hypothesis of the formation of the moon's craters.

The speed of fall of the meteorite could not have exceeded several hundred meters. Actually, from the statements of several witnesses it was possible to conclude that the altitude of the meteorite when it started to drop sharply was 7 or 8 km. This means that the mass of an iron meteorite with a specific heat of 1.8 may not be heated to more than 300 degrees C above its normal temperature, under the condition that all energy while falling goes into heating the meteorite. Trees cannot be burned at this temperature. The substance of the meteorite might reach a plastic condition and give fragments with ragged or twisted edges, which would be difficult to expect with cold treatment of an iron mass of crystalline structure and therefore rather brittle. The speed obtained exceeds that of sound, as a result of which a compression of air must have formed in front of the mass of the meteorite and carried along with it. One may arrive at the same value

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of speed on the basis of the investigation of the phenomena associated in the formation of the crater field. The mass of the meteorite which formed Crater No 1 must have been approximately 30 tons. This is equivalent to an iron sphere with a radius of one meter. Thus, the radius of the meteoritic mass which formed Crater No 1 is approximately one-fourteenth the radius of the crater itself.

Is it possible to judge, on the basis of direct excavation, the mass which formed the crater? The first data obtained on these craters gave reason to suppose that the large masses which hit them penetrated deeply, drilling passages in the rock, through which it would not be difficult to reach the masses themselves and draw them out to the surface. In actual fact, the matter was considerably more complicated. Inside and outside the craters there is a great quantity of individual fragments of the meteorite, with traces of impact against stones in the form of furrows, scratches, and deformations. These fragments were especially abundant in Craters No 11, 31, and 56, where they could be collected directly on the surface among stones, primarily inside the craters.

These fragmentary meteorites are sharply distinguished from ordinary individual meteorites whose fall had been observed previously. First of all, they had no piezoglipts (characteristic cavities and hollows on the surface of a meteorite), there was no trace of burning which develops upon the flight of a meteorite in the terrestrial atmosphere and protects it from further oxidation. For the most part these fragmentary meteorites resembled projectile splinters. They had the appearance of fragments with bent, ragged edges and there were clear traces of impact against hard rock, with furrows and pits frequently on both the outer and inner side. In rare instances spiral twisting was observed (a small fragment found in Crater No 11), which is completely inconceivable for a meteorite of coarse, crystalline structure in a cold condition. The presence of such fragments shows that they are in a plastic condition at a rather high temperature (several hundred degrees) as is apparent from other considerations as well.

With the aid of mine locators it was possible to determine the distribution of the fragments of meteorites ejected from the craters. The direction of ejection was mainly to the south, with a slight declination to the west. This was completely in accord with the direction of movement of the meteorite at its fall. Meteoritic fragments were especially abundant in Crater No 51, which was partly filled with water. The greater part of them, judged by external examination, are outside the crater and are distributed in a belt extending to the south with a declination of a few degrees to the west; this is also in agreement with the direction of fall of the meteorite. The clay flew out of the craters at a small angle to the horizon (10-15 degrees). Stones flew considerably farther and higher, tore branches off trees, and left many marks and hollows on the trunks. This material flew out radially on all sides, but mainly to the south. If a tree stood in the way, it was an obstacle for the flying stones; therefore, on the reverse side of the trees surviving after the catastrophe there was observed a decrease in the accumulated material in the form of a radially-oriented path.

The flight of fragmentary meteorites, which flew out at the time of the fall of the large meteoritic masses, was completely different. The angle of flight from the plane of the horizon was close to 60 degrees, looking from the bottom of the cone, regardless of the azimuth. This is quite evident from the torn or bevelled trunks of the trees, whose tops were torn off at the angle indicated. The angle of flight corresponds to the angle of 60 degrees at which the main mass which formed the crater fell. It is curious that the ejection at this angle occurred at all azimuths without exception. In many cases the dense forest comes to the very edge of a cone, and among numerous

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trees only one or two, sometimes several, stand with tops torn off. Thus, there is no doubt that the tops were torn off not by an air wave, which would have necessarily bevelled all the trees without exception, but by individual projectiles, that is, by meteorites.

In addition, it was discovered that the fall of the masses forming the craters was accompanied in a number of cases by a bombardment of the trees with fine particles of the dimensions of a bullet. The first example of this kind was discovered by me near Crater No 56. At a distance of 2-3 meters from its western rim there lies a fallen cedar, which previously grew on the site of the very edge of the crater. The cedar was thrown toward the west over the old trunk of a fallen tree. In the upper part of the trunk of the fallen cedar there was found an ordinary meteorite with piezpglinty, which had penetrated the wood to a depth of about 10 cm. The northern part of this trunk, partly turned toward the ground, was covered with many holes. Iron particles, which had penetrated the wood to a depth of several centimeters, were extracted from these holes. The distribution of the holes shows that the bombardment of the cedar with small fragments occured before the fall of the cedar, that is, before the formation of the crater. After this bombardment, the large crashing mass formed the crater and hurled the cedar in a radial direction to a distance of several meters; and only after its fall did the individual meteorite hit it. Thus, the small fragments which bombarded the cedar undoubtedly preceded the large mass which formed the crater, although they were connected with it.

A similar phenomenon was discovered on the south side of Crater No 31. We took note of the fact that a few trunks, with sheared-off tops and branches, standing at a certain distance from the southern side of the crater were covered with numerous holes. To investigate these holes we had to fell one of the trees. One of the holes went all the way through, which enabled us to determine rather precisely the direction of flight. This course went at a small inclination upward, and, projected back, it passed above the crater.

The small, fragmentary meteorites which bombarded the trees with a great kinetic energy present a striking contrast to the slower individual meteorites, which, as is apparent from the example of the cedar at crater No 56, were not in a condition even to penetrate the wood to a considerable depth. It must be noted, however, that such meteorites were encountered rather rarely. Apparently only a few meteoritic masses approaching the surface of the earth began to burst in the air before the moment of direct impact. The small fragments obtained, which underwent an elastic rebound against the compressed air cushion carried by the meteorite, hardly losing any speed, pierced the trees or penetrated them for several centimeters. The fragments extracted from the trees had sharp edges or a completely irregular form and did not display the slightest traces of any deformations upon impact. Their speed, consequently, could not have been very great. This is also evident from the fact that they did not cause any charring of the wood mass. The irregular facets of these iron particles were sometimes solidly filled with wood with traces of resin, but without the slightest sign of burning. One may assume with a considerable degree of probability that these small fragmentary meteorites were characterised by almost the same speed as the main mass at the moment of its fall. This speed, evidently, could not have exceeded a few hundred meters per second, which corresponds to the estimate made above on the basis of dynamic considerations. The loss to the mass which fell into the crater on account of these fragments evidently must be insignificantly small.

The even finer meteoritic material found in the clay inside some of the craters may have an entirely different significance. With the aid of a magnet, very fine particles were discovered inside Crater No 11; apparently these constituted a considerable part of the fill. It was sufficient to pass the magnet along the ground (in places where the large fragments described above, were encountered) for its poles immediately to form a brush of fine pieces

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of iron in the form of discs, needles, and dust particles. By sprinkling earth from this crater onto a piece of paper and passing a magnet under it, it was possible to observe the movement of the earth from the presence of very fine iron inclusions. In outward appearance these particles have nothing in common with the individual meteorites and evidently represent the result of maximum granulation of the meteoritic mass which formed the crater.

Such a result was obtained by external examination of the large craters. It shows that the fall of meteoritic masses occurring at a comparatively low speed, in all probability only double the speed of sound, cannot be compared to the fall of ordinary projectiles. This complicates judgment as to their magnitude. It is apparently necessary to conduct careful excavations and to remove hundreds of tons of crushed rock and clay, which fell back into the crater immediately after its formation. Such a task was beyond the powers of the expedition. It must be noted that the ordinary removal of the material from the cones can not serve the purpose, because the finely crumbled meteoritic material will inevitably be lost in the process. It is necessary to arrange the washing of all the material from inside the crater, as is done in obtaining gold. The expedition had nothing at its disposal except shovels, which were almost useless for the purpose. Nevertheless it was decided to make an attempt to partially uncover Craters No 11 and 31 (with diameters of 23.5 and 13.6 meters), which were typical of the large and medium formations of this kind.

The basis for the choice of these two particular craters was the fact that the greatest quantity of large and small meteoritic fragments was found in them.

The use of mine locators, which might have indicated the presence of large masses, did not yield any results. Therefore it was decided to conduct excavations only in separate sectors, according to the direction of fall of the meteorite. In Crater No 11 four sectors were chosen, each with an angle of diffusion of 20 degrees, toward the north, south, east, and west; the center of the crater was also designated for excavation. In the eastern sector we succeeded in reaching intact layers of porphyries, lying, as it turned out, with a small inclination toward the horizon and separated by distinct fissures. The thickness of the removed layer did not exceed half a meter. An enormous quantity of fragmentary meteorites of varying magnitude with ragged edges was found in this sector. In the western sector intact rock deposits were encountered at a somewhat greater depth, but the number of fragmentary meteorites in the given instance was comparatively very small. Intact rock deposits were also discovered in the northern sector, where small stones with a large admixture of clay predominated; a certain number of meteoritic fragments were also found here. But here excavations were not conducted over the entire extent of the sector, so the result cannot be regarded as fully reliable.

The southern sector required the most work of all. The thickness of the fill was no less than 1 meter, and a tremendous quantity of fragmentary meteorites was discovered among the large fragments of porphyries. Even here, however, we reached intact deposits of rocks in the form of powerful slabs which there was neither the possibility nor the necessity to move. Finally, the same result was evident for the very center of the crater as well: solid slabs of porphyries. Thus one apparently must come to the conclusion that there is no large mass in thes crater. The large fragments of meteorites which might have been extracted as a result of excavations over the entire extent of the inside surface of the crater would presumably amount to 3 or 4 tons. This, apparently, is too small for a crater of such a size. A certain portion of the mass, certainly, was hurled out of the crater and buried under a solid heap of clay and stones. One may think that a much larger part of the original meteoritic mass was crushed into very small pieces and scattered over the ground.

Excavations in Crater No 31 were conducted only in the direction of the meridional cross section, but the result was the same. In the southern part of the cross section a very large quantity of iron fragments of meteorites was found; in the northern part, considerably fewer. In both cases, as well as in the center, intact rock deposits were reached, which indicate the absence of a large meteoritic mass.

Thus it is extremely probable that the meteorites which formed the craters were not preserved in the form of large masses penetrating deeply, but were crushed into small fragments. This is in conformity with their coarse structure. As was established by chemical analysis conducted first at the Chemical Laboratory of the Far Eastern base of the Academy of Sciences of the USSR in Vladivostok, and later at the Geochemical Laboratory in Moscow, the meteorite was distinguished by an extremely low nickel content (5.8 per cent Ni, 0.34 per cent Co); and it had an octahedral structure with large amounts of interstitial material with a comparatively low cohesion.

Excavations of small cones of a diameter of 1-2 meters showed a completely different result. These cones were formed somewhat later than the large craters; in other words, the meteorites which created them fell at lower speeds than the large masses which crushed the rocks. This may be easily established by studying the distribution of the material hurled out of the various craters.

As a result of the lesser speed of fall of the small meteoritic masses, these latter were able to be preserved for the most part, although they displayed a tendency toward granulation. The excavations of small cones conducted by Krinov, Malinkin, and Lyubitskiy were very instructive in this respect. Thus, for example, a meteorite 2.7 meters in diameter and 0.8 meter deep with characteristic piezoglints, was discovered with the aid of a mine locator in cone No 79; three other meteorites were found in the vicinity, at distances of 5.2, 4.7, and 2.9 meters from it. When these three meteorites were placed together, their surfaces fitted together very well. Thus the original mass was reestablished with dimensions of 72 x 37 x 30 cm. Moreover, a considerable quantity of smaller fragments was found in the same cone.

Meteorites were extracted whole from cones of smaller dimension. These meteorites, extracted from a certain depth, represent a transition to bodies of even smaller dimension, which, as a rule, formed only small depressions or lunes; they lay in them openly, or, as happened very frequently, they sprang out of them for some distance. Many similar individual meteorites were found by Krinov, Livari, Shikulin, and other members of the expedition when they inspected the crater field and its vicinity, primarily in a northern direction.

All similar meteorites presented a solid mass covered with piezoglints as a result of irregular fusion in the atmosphere, but without the slightest traces of granulation. It is curious that the large craters are concentrated in a comparatively small area (about 1.4 km), and are mixed with small cones of all dimensions. Individual meteorites were also discovered repeatedly in the crater field itself, lying in small lunes or simply on the ground in the most unexpected places, for example, under the roots of trees, around individual fallen trunks, etc. Individual meteorites were also encountered far beyond the boundaries of the crater field in a northern direction. A combing of the taiga for a distance of 4 km to the north showed finally, a gradual decrease in the number of meteorites, but the limit of their extent was not reached for certain. We were even less successful in exploring the region to the northeast of the crater field, where it was necessary to halt before extensive marshy places in the valley of a stream flowing into the Khanikheza River. In all, 256 individual meteorites were found with well-defined piezoglints at various stages of their development. A few specimens are of interest from the point of view of judging the gradual development of piezoglints and the origin of the crust of tempering.

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Small meteorites frequently displayed deep and narrow fusions with intrusions of crystalline structure and with piezoglints, broad and undulating on one facet, small and narrow on another. These peculiarities permit one to establish how the separation of the fragments from the meteoritic lumps in their flight in the atmosphere occurred, for the facets with larger piezoglints evidently represent a part of the larger mass.

We must now characterize the general impression obtained from the crater field. By a fortunate circumstance, it is located near the Iman-Ulunga air route and may be easily observed from a plane. Owing to just this circumstance, the place of fall of the Sikhote Alin meteorite was quickly discovered. As early as 13 February, the very day after the fall of the meteorite, an aviator, Semenov, of the Iman airdrome flew over this field and took note of it, but did not make a full report. On 15 February this field was found by aviators Firtsikov and Ageyev of the Khabarovsk Geological Administration; later, as already indicated, it was visited by geologists of the same administration simultaneously with F. K. Shipilin, director of the geology section of the Far Eastern base of the Academy of Sciences of the USSR. The field was photographed from the air by motion-picture cameraman Prok. In June of the same year it was again photographed by a member of our expedition, N. B. Divari. By this time the taiga was already covered with dense vegetation. The tops of the individual trees surrounding the crater field are plainly visible on Divari's photographs, but are almost imperceptible at the actual spot where the craters are located. Numerous tree trunks stripped of their branches attract one's attention; belts of fallen trees radiate from the craters, which stand out against a general dark background in the form of broad, white rings with a darker center. The radial ejection of the same white material is noticeable in the form of separate rays, primarily in one direction. Such a selectivity in the ejection of material is also confirmed by the direct examination of the entire crater field. In some places, for example, between Craters No 20, 31, and 11, there extends an almost continuous strip of fallen trees, as if a gigantic tornado had passed here from the north.

The felled and mutilated trees in the area of the crater field merits careful study by further expeditions. This illustrates the complicated play of aerodynamic forces which appear with the fall of large meteorites. As has been shown, the speed of their fall exceeded the speed of sound. Under such conditions an air cushion must have been moving in front of the meteoritic mass with the force of compressed air, which continously spilled along the sides, creating a strong system of whirlwinds. With a cosmic speed of movement in the terrestrial atmosphere of the order of tens of kilometers per second, the compression of gases in front of the head of the meteorite occurred so intensively that their temperature was capable of rising to 3 or 4 thousand degrees. These gases, a mixture of air and incandescent vapors of iron, quickly spilled along the sides, forming the visible head of the meteorite with linear dimensions of 300-500 meters, that is, enormous in comparision with the dimensions of solid meteoritic masses. As a result of adiabatic expansion, this gaseous wrapper, opaque and brightly gleaming, cooled quickly, which set a limit to its visible dimensions. As a result, the iron-nickel vapors quickly condensed and, lagging behind the head of the meteorite, formed a dark swirling trail, reflecting the whirlwinds which inevitably developed behind the flying mass. The material of this trail, being at first opaque, admitted red light primarily, and therefore must have consisted of particles of iron very small in comparison with the length of the light wave. The physical form of this material may be reproduced experimentally.

At the moment of fall of the meteorite, the conditions must have become even more complicated. When the compressed air driven forward by the falling mass encountered an obstacle in the form of the surface of the earth, it must

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have exerted a strong reaction on the ground and on the meteorite itself. The small fragments which flew with great energy (sometimes piercing trees), so far as one can tell, were a result of this reaction, and rebounded from the elastic air layer even before the fall of the meteorite. The large meteoritic mass pierced this compressed air layer and struck the rock deposits, crushing them, and burying itself to a shallow depth.

The rich material collected by the expedition must yet undergo careful processing. The determination of the speed of movement of the meteorite in space and at the moment of fall not only will make it possible to calculate its orbit and determine its movement in the heavens before its encounter with the earth; it will also provide indispensable prerequisites for a discussion of the formation of craters, and consequently of the total mass of the meteorite. If the total mass of the meteorite, as seems highly possible, was of the order of one thousand tons, then the Sikhote Alin meteorite could have been noticed in the form of an asteroid of the fifteenth magnitude, and at a distance three times greater than the radius of the lunar orbit.

KEY TO PHOTOGRAPHS

[The photographs in this article have not been reproduced, but are available in the original document at Foreign Documents Branch, CIA.]

1. Crater field covered with stones and tree trunks.

2. Tree trunk with many holes produced by small meteoritic fragments.

3. Part of a crater 28 meters in diameter.

4. Fragments of meteorites found inside a crater.

5. Trunks of trees with sheared-off tops and branches, pierced by meteorites.

6. Fragments of meteorite (placed beside a hammer for comparison).

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